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**NASA
SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)**

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COMBINING ASCENT LOADS

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MAY 1972

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all published monographs in this series can be found at the end of this document.

These monographs are to be regarded as *guides* to the formulation of design requirements and specifications by NASA Centers and project offices.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was W. C. Thornton. The author was J. C. Houbolt of Aeronautical Research Associates of Princeton. A number of other individuals assisted in developing the material and reviewing the drafts. In particular, the significant contributions made by the following are hereby acknowledged: V. L. Alley, Jr., of NASA Langley Research Center; E. S. Criscione of Kaman Corporation; D. E. Hargis of The Aerospace Corporation; D. L. Keeton, J. S. Keith, and K. A. McClymonds of McDonnell Douglas Corporation; G. Morosow of Martin Marietta Corporation; L. A. Riedinger of Lockheed Missiles & Space Company; and M. E. White of TRW Systems Group/TRW Inc.

NASA plans to update this monograph periodically as appropriate. Comments and recommended changes in the technical content are invited and should be forwarded to the attention of the Structural Systems Office, Langley Research Center, Hampton, Virginia 23365.

May 1972

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GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to provide a uniform basis for design of flightworthy structure. It summarizes for use in space vehicle development the significant experience and knowledge accumulated in research, development, and operational programs to date. It can be used to improve consistency in design, efficiency of the design effort, and confidence in the structure. All monographs in this series employ the same basic format - three major sections preceded by a brief INTRODUCTION, Section 1, and complemented by a list of REFERENCES.

The STATE OF THE ART, Section 2, reviews and assesses current design practices and identifies important aspects of the present state of technology. Selected references are cited to supply supporting information. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the CRITERIA and RECOMMENDED PRACTICES.

The CRITERIA, Section 3, state *what* rules, *guides* or limitations must be imposed to ensure flightworthiness. The criteria can serve as a checklist for guiding a design or assessing its adequacy.

The RECOMMENDED PRACTICES, Section 4, state *how* to satisfy the criteria. Whenever possible, the best procedure is described; when this cannot be done, appropriate references are suggested. These practices, in conjunction with the criteria, provide guidance to the formulation of requirements for vehicle design and evaluation.

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COMBINING ASCENT LOADS

1. INTRODUCTION

During ascent, a space vehicle experiences loads from a variety of sources that have both a time-varying property and marked statistical variability. Since many of these sources act simultaneously, a problem exists in combining the loads to determine the critical loads used for structural design of the vehicle. In general, then, the structural efficiency and integrity of all ascent vehicles depend on a rational procedure for analytically combining loads.

Inadequate combination of the loads may result in a structure of inadequate strength or of excess strength (and weight). The simple addition of maximum loads without regard to phasing, for example, may lead to overdesign. Specific cases of vehicle failure ascribed to inadequate attention to combining loads include the structural breakup of an atmospheric research vehicle because certain venting loads were not considered, and the failure of a booster vehicle due to lack of attention to buffeting loads acting simultaneously with the other ascent loads.

This monograph presents criteria and guidelines for combining the loads that develop during the ascent phase of flight, which is defined as the portion of flight extending from the moment before launch release through final stage separation. A load is defined as the dependent load that is produced at a particular time at a designated point of the structure due to the externally applied loads and associated reacting inertial forces. The name given to the load indicates its source. Wind loads, for example, are the resulting loads at a moment in time at a designated location within the vehicle due to the external forces and associated reactive inertial forces resulting from the environmental wind disturbances. Load sources are differentiated from loads as being only the applied forces from independent external causes.

The load-combining process for ascent flight is quite intricate because of the diversity of the load sources. At a particular time, for example, the vehicle may experience simultaneous input load sources as follows: a quasi-steady axial load from the rocket engine, a superimposed random axial load due to unsteady rocket burning, external random aerodynamic loads due to winds and gusts, control-force loads due to steering and reaction to the winds, and impulsive load due to the firing of some pyrotechnic device. The problem is made more complicated because many sources (e.g., winds and gusts) are known at best in only a statistical sense. In addition, the vehicle is a time-varying reactive system with respect to its parameters such as mass. Further,

inertias, natural modes, and frequencies change abruptly at staging. The load-combining process is, therefore, usually rather involved.

The monograph mainly discusses the primary load-carrying members of the structure, which include the basic tanks and interconnecting members, engine support mounts and connections to tank structure, transition structures between stages, payload shrouds, and the basic support points at separation planes. Explicit consideration of the payload, internal components, and component mounting plates or brackets is not included in this monograph, although the guidelines may also apply to them. Flexible-body effects and the associated aeroelastic effects are assumed to be accounted for in the response treatment. Such instability phenomena as aeroelastic divergence, flutter, control-loop instability, and limit-cycle oscillations (except for pogo) -- usually viewed as being catastrophic and hence to be avoided -- are not considered to be within the combined-loads problem.

Individual load sources that enter into the load-combining process are discussed only in terms of their broad characteristics; detailed treatment of some of these load sources can be found in other monographs (refs. 1 to 6).

2. STATE OF THE ART

To approach the problem systematically, it is convenient to classify the loads into three phases: launch, powered flight, and staging. Figure 1 identifies representative load sources that can occur in each phase. These sources combine in various ways to create the structural loads that govern booster design. Generally, the most critical load combination arises during the powered-flight phase.

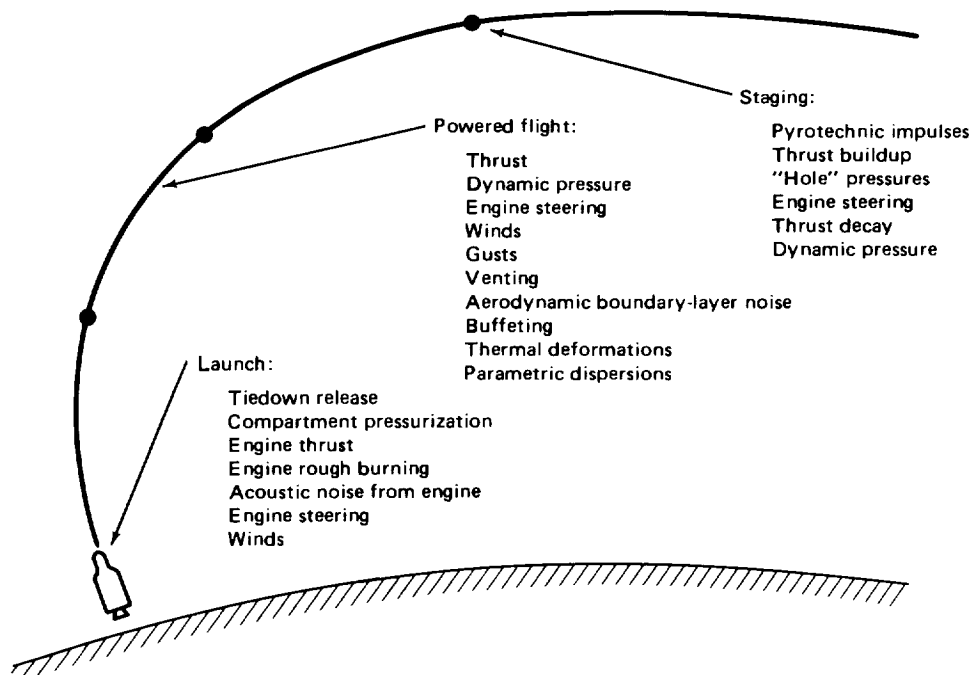


Figure 1. — Representative load sources during ascent flight.

Although combined-load analyses have been made on each launch vehicle that has been built and flown (refs. 7 to 14), no established rules or routine procedures for combining loads have been published. Combining loads for each new application is thus still largely a matter of engineering judgment, and the techniques used are mostly the specific preferences of individual program organizations. Often, too, the first flights of a new vehicle reveal an additional or unexpected load source; further combined-load analyses may thus have to be made after the vehicle has been constructed to check whether its design is adequate. Some combined-load approaches that have been employed are reviewed and assessed in the following sections.

2.1 Techniques for Combining Loads

2.1.1 Launch

Although many load sources are encountered during launch, it appears that only a few of the load combinations that act during this phase have been critical for the primary structure of vehicles that are launched from an open pad. For example, combined loads induced by engine ignition, tank pressurization, and launcher release have been critical in some vehicle designs, such as the Saturn V configuration and Atlas/Agena booster. By contrast, certain other launch loads, such as those arising from rough burning or engine exhaust noise, have been found to be critical only to design of vehicle components and the payload.

Techniques for combining loads that arise during the launch phase do not differ greatly from those needed for the powered phase of flight and the problems are somewhat less involved since the predominant launch loads are usually deterministic rather than probabilistic.

2.1.2 Powered Flight

The loads which combine during powered flight generally produce the critical structural design conditions. Since the vehicle involved is considered a nonlinear system with time-varying coefficients which can have intricate fuel-sloshing modes, many rigid- and flexible-body degrees of freedom, and rather involved control loops and subsystems, and since the loads are many and diverse, the powered-flight phase is also one of the most difficult to treat analytically in a rational way. Many attempts have been made to classify the load sources and to develop simplified schemes for establishing the vehicle response. Opinions vary widely, however, as to how individual load sources should be handled and how response evaluations should proceed.

2.1.2.1 Load Sources

In general, the load-combining problem cannot be treated independently of the load sources because the actual combining technique depends largely on the nature of the load inputs. Four load sources merit brief discussion: winds, gusts, air density, and parametric dispersions.

Winds. Winds are generally the source of the most severe loads (ref. 6). It has been common to represent horizontal winds by the techniques of synthetic wind profiles, measured profiles, and nonstationary statistical descriptions. Synthetic winds (e.g., refs. 15 and 16) are essentially simple, curve-type representations of measured profiles.

Measured or “fine-grained” wind profiles (e.g., refs. 17 to 21) are used when more accurate or “realistic” evaluation of vehicle response is desired. Nonstationary statistical descriptions (refs. 22 to 27) express wind data in terms of a “covariance wind function.” These statistical approaches have had limited application, and computational effort is quite extensive.

Gusts. A common practice is to separate gusts from winds. The means for analyzing gusts are discussed in reference 6. Gusts are often considered to act normal to the vehicle axis and are assumed to be represented by simple, discrete time functions. In other cases, gusts are treated stochastically and are handled by power spectral techniques.

Air Density. Intimately associated with winds, gusts, and vehicle response is the environmental parameter, air density, which is characterized by marked statistical variability. Determination of the influence of day-to-day changes in air density on load statistics is a difficult and questionable task because of the way air density appears in the equations of motion (it appears on both the input and the response side of the equation and is a multiplier of the input random variables, winds and gusts, as well). The main techniques used for treating the dispersion in air density are to calculate the loads for a number of different atmospheres, (ref. 28) or to choose a “worst” case for density which, presumably, will lead to loads on the conservative side.

Parametric Dispersions. The dispersions (or tolerances) in vehicle parameters which lead to dispersion loads include the following:

Mainly vehicular

- Aerodynamic force coefficients (normal and drag)
- Aerodynamic moment coefficients
- Structural weight
- Misalignments of structure and thrust vector

Vehicular and operational

- Fuel weight
- Autopilot displacement gain
- Autopilot rate gain

- Pitch program
- Center-of-gravity
- Fuel consumption rate
- Thrust

Of these, the misalignments, pitch-program, thrust, and aerodynamic parameters generally lead to the largest dispersion loads. As an indication of the importance of these loads relative to winds and gust, experience has shown that for guided-vehicle designs the contribution to the bending moment of some of the various sources is roughly as follows:

<u>Source</u>	<u>Relative Magnitude</u>
Winds	1.00
Gusts	0.25-0.34
Misalignments	0.05-0.15
Pitch command and thrust	0.05-0.15
Aerodynamic dispersions	0.05-0.15

Since mean load and dispersion loads are often referred to in the process of combining loads, and since there is no universal definition of their meaning, and even controversy over how to include mean response to winds and gusts, some clarification of their meaning is in order.

In figure 2, the solid curve represents, say, the time history of bending moment that is obtained deterministically at a particular station along a vehicle, using a chosen wind profile, and choosing nominal values for the various parameters μ_n (herein, deterministic means the direct evaluation of response to a prescribed load). The curve represents the “mean value” for bending moment that is used in the load-combining process.

It should be noted that the mean value in the sense used here is a time-dependent quantity; the combining process seeks to establish the maximum combined loads, which may or may not occur at the time one of the mean-load values reaches its maximum. The mean value may be the time history as obtained from a single wind-input profile, it may represent the average of the response time histories obtained from a number of different wind profiles, or it may be the envelope curve of these time histories. No consistent approach has been established for determining the mean value.

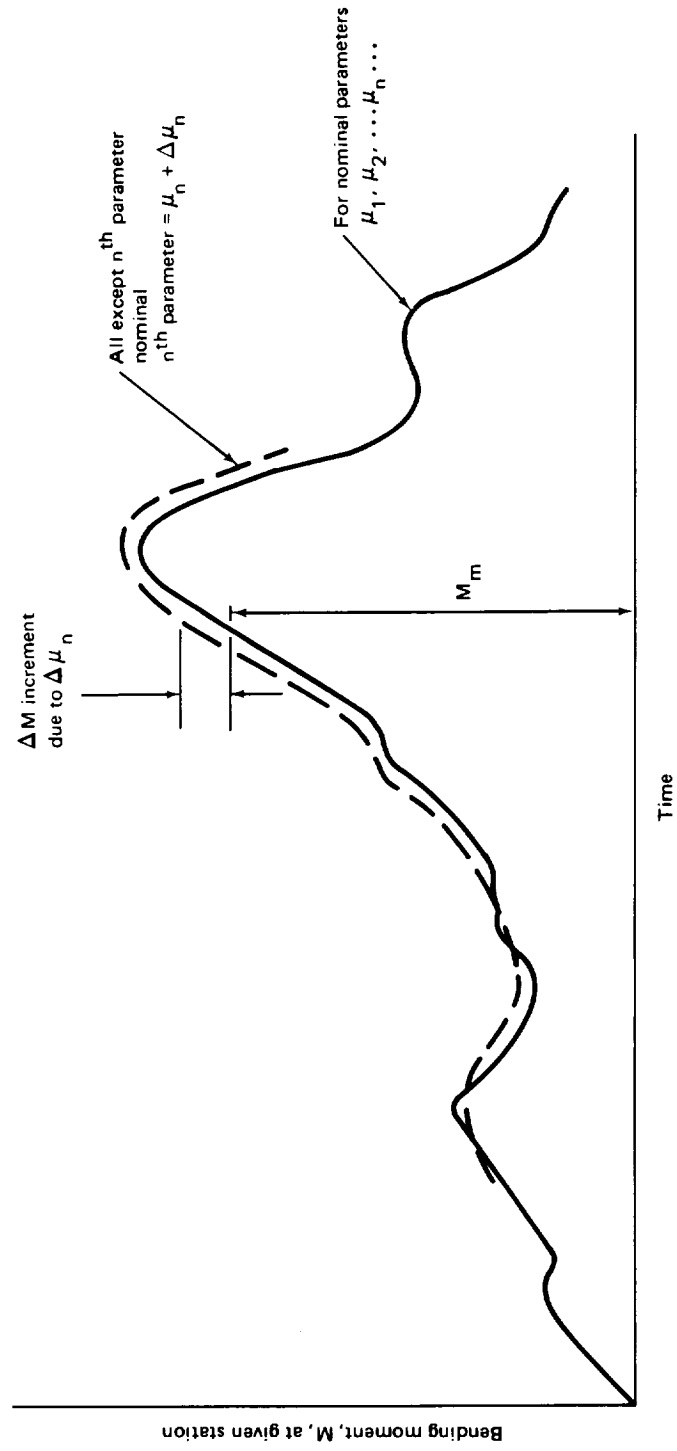


Figure 2. – Illustrative determination of bending-moment dispersion due to a given parametric dispersion.

The dotted line in figure 2 is the result obtained by changing one parameter by an incremental or “dispersion” value, holding all other parameters the same. The ΔM , then, is the dispersion bending moment due to the assumed parametric dispersion. Other parameters are handled similarly. When the $\Delta\mu_n$ is taken as the rms variation of the μ_n parameter, the ΔM becomes the associated rms variation in the bending moment. Further insight into the determination of dispersion loads may be gained from reference 29.

2.1.2.2 Analysis

The means for evaluating vehicle response to winds, gusts, and dispersion effects are varied (ref. 6). They include treatment of the vehicle response in complete and detailed deterministic form (refs. 30 to 36); simplified treatments which use a “wind” influence function in conjunction with a perturbation analysis (refs. 25, 37, and 38); non-stationary statistical methods involving a linearized treatment (refs. 22, 24, and 26), and power spectral treatments (refs. 39 to 41). The means of combining loads depend somewhat on the analytical method used (e.g., in the detailed treatment, winds and gust loads are included together; in the simplified approaches, winds and gusts are treated separately; in the statistical approaches, statistical measures for wind and gust loads are used in place of “mean” loads).

One of the simplest combined-load treatments that has been used in preliminary design considerations is an assumed hard-over engine condition at a certain critical flight period, such as the maximum dynamic pressure period. The vehicle axial load and the bending-moment loads due to the hard-over engine condition are simply added deterministically to arrive at the total combined loads. This method has been used on some smaller boosters, but it does not appear to be used on the large launch vehicle configurations.

Another simplified approach used for preliminary design analysis is to assume a 5° to 10° angle of attack at the maximum dynamic pressure condition. The vehicle loads and bending moment are then evaluated deterministically for this design condition.

Another preliminary design procedure mentioned in reference 6 involves the use of a perturbed trajectory obtained by varying certain vehicle characteristics. For example, the programmed pitch rates can be increased or an upper tolerance on the thrust and a lower tolerance on the aerodynamic drag can be incorporated, usually leading to a more severe dynamic-pressure environment and, hence, to conservative wind loads.

A method of combining loads often mentioned in the literature but apparently never used is simply to add the magnitudes of the loads from the various load sources without regard to simultaneity or probability of occurrence (ref. 42). The consensus of

most investigators is that this approach for combining quasi-steady loads is too conservative and would lead to overdesign.

In an attempt to be more realistic, specifically to account for the simultaneity of action of the various load sources and the fact that many of the loads are statistical in nature, load-combination studies are now usually based on an equation of the form

$$y = y_{\mathbf{W}} + y_{\mathbf{G}} \pm \eta \sqrt{\sigma_{\mathbf{W}}^2 + \sigma_{\rho}^2 + \sigma_{\mathbf{B}}^2 + \sigma_{\mathbf{D}}^2} \quad (1)$$

where $y_{\mathbf{W}}$ is the response mean load due to winds, $y_{\mathbf{G}}$ is the load due to gusts, η is a factor for standard deviations (often assumed to be 3), $\sigma_{\mathbf{W}}$ is a root-mean-square (rms) wind dispersion load (if involved), σ_{ρ} is the rms load value due to air density dispersions, $\sigma_{\mathbf{B}}$ is the rms load value due to buffeting, and $\sigma_{\mathbf{D}}$ is the rms load value due to all other dispersion effects. For noncorrelated dispersion loads, $\sigma_{\mathbf{D}}$ may in turn be given by

$$\sigma_{\mathbf{D}}^2 = \sigma_{\mathbf{C}_D}^2 + \sigma_{\mathbf{L}}^2 + \sigma_{\mathbf{W}_S}^2 + \sigma_{\delta}^2 + \sigma_{\mathbf{W}_F}^2 + \sigma_{\mathbf{K}_\theta}^2 + \dots \quad (2)$$

where the subscripts refer to dispersion parameters; the examples of dispersion parameters shown in this equation are, respectively, drag coefficient, airload distribution, structural weight, misalignments, propellant weight, and autopilot gain. Bending moment and axial load are usually handled separately, each by an equation analogous to equation (1).

Figure 2 relates to equations (1) and (2) as follows. The \mathbf{M} value of figure 2 is the $y_{\mathbf{W}}$ of equation (1). If the $\Delta \mathbf{M}$ of figure 2 is, for example, the result of using a drag coefficient which includes a 1- σ deviation, then the $\Delta \mathbf{M}$ is the $\sigma_{\mathbf{C}_D}$ value of equation (2). If consideration is restricted to a single wind-input profile, such as a synthetic profile, there is no $\sigma_{\mathbf{W}}$ in equation (1). If a number of profiles are considered, $y_{\mathbf{W}}$ is the average mean value, and $\sigma_{\mathbf{W}}$ is the average mean value, and $\sigma_{\mathbf{W}}$ is associated with the dispersion of the various mean values.

The application of equation (1) implies many assumptions, some of the more important being that:

1. The use of $y_{\mathbf{W}}$ is adequate for representing the statistical nature of the winds. The winds are not only one of the severest load sources but also are one of the most random; this randomness is therefore presumed to be reflected in the basic means available for evaluating $y_{\mathbf{W}}$; namely, (a) by using

some synthetic profile but evaluating the response deterministically, (b) by statistically analyzing the results that are obtained through use of a large number of measured wind profiles to obtain both a y_W and a σ_W (the so-called statistical loads survey method), or (c) by using nonstationary statistical methods.

2. The gust load y_G and the wind load y_W are indeed separable.
3. Enough is known to allow determination, with some degree of confidence, of the rms values of the dispersion parameters, and, in turn, of their rms load dispersion values.
4. The method used for handling air density is adequate.

The application of equation (1) is made even more complex when wind and dispersion loads are established as response values in the pitch and yaw planes (ref. 42). The load value due to winds and gusts is obtained as the resultant of the pitch and yaw plane values, y_P and y_Y (fig. 3). Pitch and yaw dispersion loads D_P and D_Y are also obtained, and a current practice (although not quite correct) is first to assume that the envelope of these dispersion loads is an ellipse, and then combine the resultant loads as shown in figure 3.

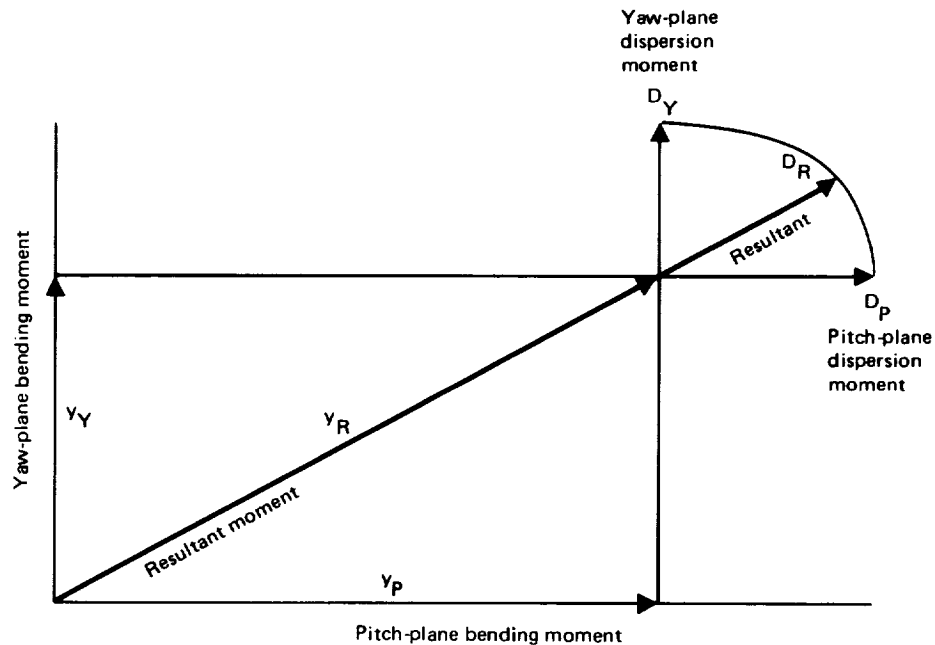


Figure 3. — Combined pitch-and-yaw plane responses.

References 8, 12, 28, 42, and 43 reflect the treatment of combined loads through use of techniques related to equation (1). Various hybrid forms of this equation have been used in combined-load design studies (refs. 8 and 42), such as the following equation:

$$y = y_W + \frac{1}{3}y_G + 0.415y_B + \sqrt{\left(\frac{2}{3}y_G\right)^2 + \left(0.585y_B\right)^2 + y\frac{2}{D}} \quad (3)$$

where y_G and y_B are the total loads due to gusts and buffeting, respectively, and y_D represents the dispersion loads. The logic behind this equation seems to be connected with the interpretation that is depicted in figure 4, which refers to one of the random load components comprising the combined load (e.g., the load due to buffeting). The concept considers an envelope curve of the actual time history, then develops design loads in terms of the mean or moving average value and an rms value of this envelope; the term $0.415y_B$ in equation (3) relates to y_{em} in figure 4, and the term $0.585y_B$ to σ_e . This concept is considered without adequate foundation and is not recommended for use.

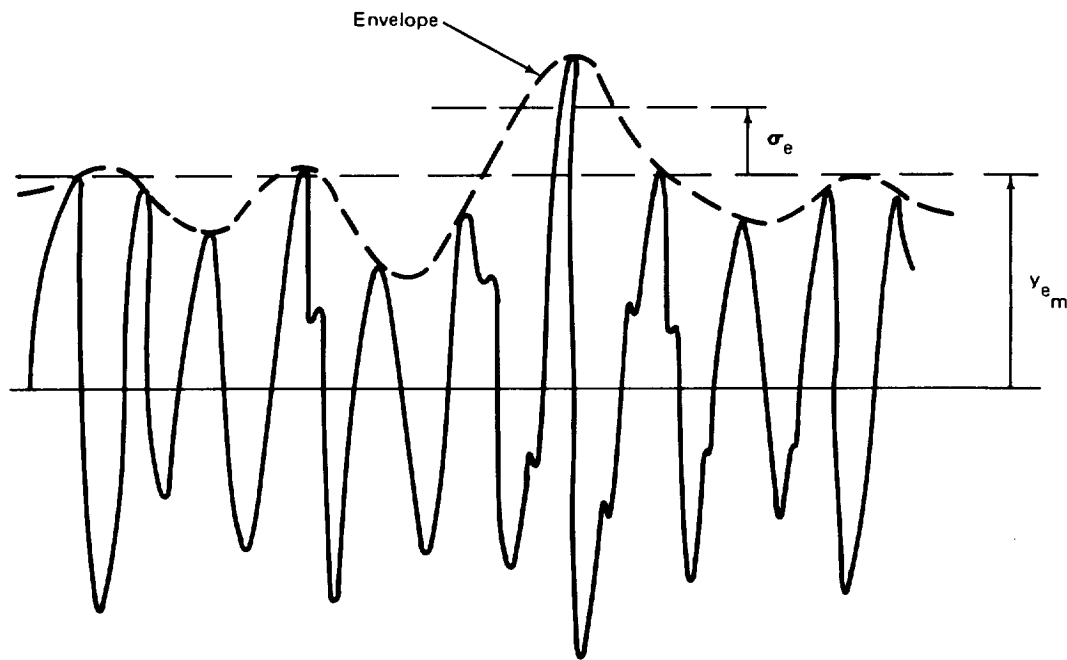


Figure 4. — Hybrid representation of response.

References 40 and 44 discuss briefly the following altered form of equation (1):

$$y = y_W + \eta \sqrt{\sigma_W^2 + 2\gamma\sigma_W\sigma_G + \sigma_G^2} \quad (4)$$

but no applications appear to exist. The equation assumes that the gusts and winds are correlated, as defined through a correlation factor γ (ref. 45). The means for separating winds and gusts, or establishing σ_W and σ_G , is not clear, and at the moment the equation appears to have little usefulness.

Essentially, the determination of axial load, shear load, and bending moment through means of an equation such as (1) represents the first part of the combining problem. The second part of the problem is that of combining the axial shear and bending loads with significant loads from such other sources as residual "pogo" oscillations, venting, tank or compartment pressurization, or local buffeting.

The mention of pogo in the load-combining process may seem odd, since a design objective is to avoid any catastrophic instability such as divergence, flutter, control-loop instability, or pogo. In some designs, however, pogo-type oscillations are difficult to eliminate completely and thus any residual or low-level pogo mode or limit-cycle oscillation that might be present is treated as an independent load source. Venting and tank pressurization may lead to hoop tension and axial loads, and may produce local bending effects.

Buffeting loads (refs. 1, 46, and 47) may involve large-scale shed vortices which affect the bending of the vehicle as a whole; in this case, the buffeting effects appear as in equation (1). But buffeting may also involve a small-scale turbulence flow affecting the structure only in a local sense, as in separated flow or a turbulent boundary layer; allowance must thus be made for this more localized effect.

With the loads and the details of the geometry at a specific point, the combined stress can be determined. Because stress analysis is beyond the scope of this monograph, it is not pursued further except to mention that it involves consideration of the stresses resulting from all six components of the combined force and moment vectors, each of which is a random quantity.

It should be noted that it is not strictly correct to use an equation like (1) to determine dispersion effects separately for bending moments, shear loads, and axial loads, and then to combine the results, because these dispersions are not generally independent statistically. It is more appropriate to determine all of the dispersions due to wind, all those due to gusts, and so on, and then to obtain the composite dispersion effects from all the individual dispersions by a single root-sum-square operation. Fortunately, little error appears to result in most cases when the dispersion effects of axial and lateral loads and bending moments are established separately. If the structural response

is being established by a redundant analysis (such as a finite-element approach), wherein loads or stresses at a point are determined directly, this kind of error is avoided. However, the computation by the finite-element approach may be prohibitive for a complex system with a large number of independent load sources, particularly when these sources are treated statistically.

Critical combined-load situations may sometimes arise because of special mission requirements. In a particular vehicle design, for example, trajectory considerations associated with range safety required the vehicle to execute a sharp “dog-leg” maneuver which resulted in a large angle of attack and high, unsymmetrically distributed aerodynamic temperatures on the structure. The steering loads along with the aggravated aerodynamic loads that resulted from the thermal deformation were found to be the design combined-load condition; in this case, the combining was deterministic in nature.

The effects of elevated temperatures on material properties (and, in turn, on loads due to changes in stiffness) are often examined but are not usually found to be a problem. Thermal stresses due to temperature gradient and reduction in allowables due to temperature are not generally considered to be part of the combined-load analysis but rather are accounted for later in the stress-analysis phase of the design.

Studies pertaining to powered flight often discuss load results in terms of probability of occurrence or probability of exceedance. Little credence can be given to these probabilities, however, because little is known about the actual statistical distribution of most of the load sources. Care should be taken, therefore, not to attach undue significance to the probability numbers given.

2.1.3 Staging

No set procedure is followed for determining the combined loads during staging or separation. Usually, most of the load sources can be identified, but the sequence of load application and how the loads combine depend on both the vehicle elements and the separation techniques used. Procedures for establishing separation loads are therefore usually tailored to each vehicle; analysis proceeds mainly along deterministic lines (ref. 4).

Sometimes it is impossible to identify or anticipate certain loads that should be included in the combining problem. An example is the case presented in figure 5. In this instance, flight tests of the vehicle revealed that a side force, not anticipated originally, was developing in the engine nozzle. The origin of the side force was later found to be a separated flow condition on one side of the nozzle during thrust buildup [(a) in fig 5.]. Figure 5(b) shows the loads that were considered in the subsequent combined-load treatment (the combined axial force due to engine ignition and to

“firing-in-the-hole,” as in the original combined-load treatment) and the unanticipated side force that developed due to the fire-in-the-hole operation. The loads were analyzed separately for longitudinal and lateral response and were then added without reference to phase to obtain the combined loads.

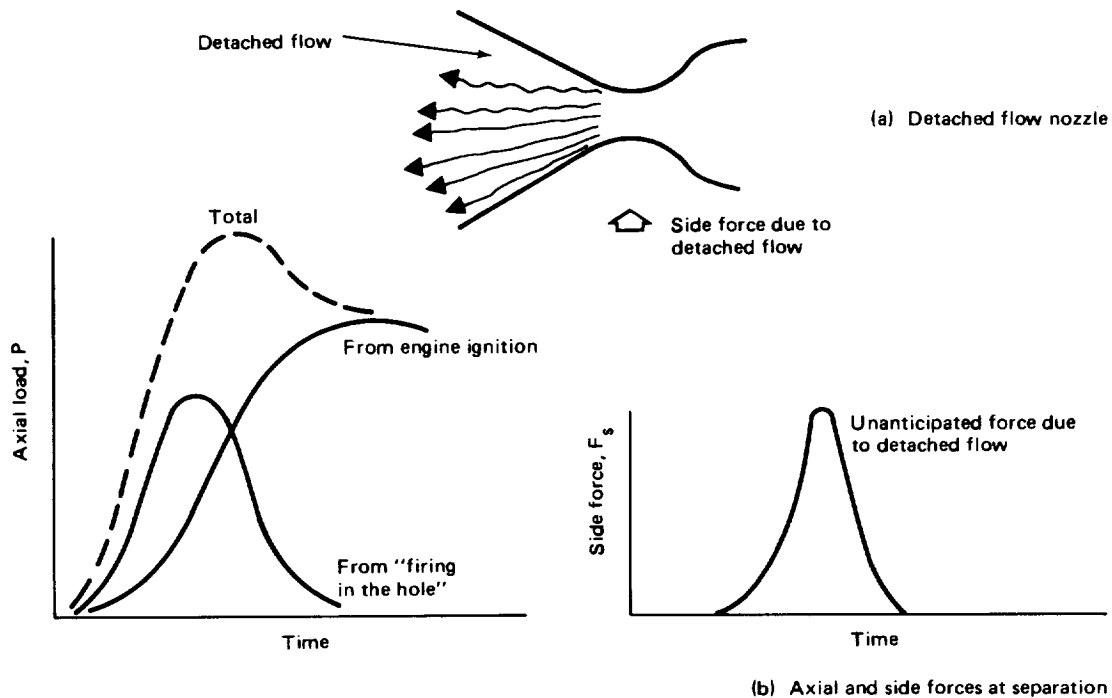


Figure 5. – Specific case illustrating unanticipated combined loads during separation.

2.2 Testing

Tests which explicitly verify the technique for combining loads do not exist. Actual flight tests are the only tests which can yield realistic combined loads. Combined-load ground tests are generally made on structural components, however, mainly to verify that the structure can withstand the chosen design loads. The applied test loads reflect primarily the axial load and bending moment, but sometimes differential pressure load and heat “load” simulated by heat lamps are also applied.

Even though isolated flight tests cannot be used for explicitly checking the technique used for combining loads, analyses of measurements obtained during a large number of flight tests could be used to raise the confidence level regarding the combining process. A primary reason for making load measurements during flight tests is to see how the measured loads compare with those used in design, and to check whether other unexpected load sources develop. References 11, 13, and 14 present the results of certain flight studies of this type.

3. CRITERIA

The loads that will be encountered by space vehicles during ascent flight shall be rationally combined in analysis to obtain the total loads that develop in the primary structural members of the vehicle. The probability and simultaneity of occurrence shall be accounted for, and where load sources with statistical variation are involved, acceptable statistical procedures shall be used in the analysis.

3.1 Load Sources

All significant load sources acting on the vehicle, and all combined and repeated loadings during launch, powered flight, and staging shall be identified. Load sources shall include at least the following, as applicable:

Launch

- Tiedown release
- Compartment pressurization
- Engine thrust transient
- Engine rough burning
- Engine acoustic noise
- Engine steering
- Winds
- Parametric dispersions, including center-of-gravity offset and thrust misalignment

Powered Flight

- Thrust
- Density and dynamic pressure
- Engine steering
- Winds

- Gusts
- Venting
- Aerodynamic boundary layer noise
- Buffeting
- Thermal deformations
- Parametric dispersions

Staging

- Thrust decay
- Thrust buildup
- “Hole” pressures
- Engine steering
- Density and dynamic pressure
- Flow separation
- Wake interaction
- Parametric dispersions

Variations of the loadings with time, any statistical variations in the magnitude of the loadings and their correlations, and the effect of elevated temperature on stiffness shall be accounted for as appropriate.

3.2 Analysis

The combining of loads shall be rational and conform to acceptable statistical procedures, with the statistical makeup of the loads, their correlation, and the simultaneity of their occurrence being accounted for as necessary. Load-response analyses for establishing the loads that are used in the combining process shall include an adequate representation of the vehicle response equations to cover the frequency spectrum of the external load sources and shall conform to well-established structural-analysis procedures.

4. RECOMMENDED PRACTICES

4.1 Load Sources

In preparation for the load-combining process, all load sources that are likely to be encountered by the vehicle should be identified. Figure 1 indicates the load sources that have most generally been involved, but care should be exercised to examine whether other load sources might be involved for the particular vehicle under consideration. These load sources should then be classified into those which can be treated deterministically and those which should be handled in a statistical way. The decision as to whether time phasing is significant should also be made as far ahead as possible. Time-history evaluation of specific loads due to the load sources should then proceed in a manner consistent with the classification made. Where appropriate, linearized or perturbation solutions should be employed in the load response analyses to facilitate loads combining by superposition. The load results of these time-history evaluations should then be combined according to the guidelines in the following sections.

4.2 Combined-Loads Analysis

4.2.1 Launch

Launch loads may lead to critical design conditions for portions of the primary structure of vehicles launched from an open pad. An analysis of the combined loads at launch should, therefore, be made to evaluate whether they might be critical and also to establish their effect on secondary launch structure. The combining process, if necessary, must be tailored to the particular vehicle, although the guidelines recommended for powered flight are generally applicable.

4.2.2 Powered Flight

Generally, the loads obtained during powered flight should be combined in accordance with the following procedure. Axial load, shear, and bending moment should each be evaluated separately, according to the following equation:

$$y = y_W + y_G \pm \eta \sigma_T \quad (5)$$

where y_W and y_G are the quasi-steady “mean” loads due to winds and gusts, respectively, η is a standard-deviation factor which normally may be taken as 3, and σ_T

is the rms load value due to random load sources and parametric dispersions. In general, σ_r is given by

$$\sigma_r^2 = \sigma_W^2 + \sigma_\rho^2 + \sigma_B^2 + \sigma_{C_D}^2 + \sigma_L^2 + \sigma_{W_S}^2 + \sigma_\delta^2 + \sigma_{W_F}^2 + \sigma_{K_\theta}^2 + \dots \quad (6)$$

where σ_W and σ_ρ are the rms load values due to winds and air density, σ_B is the rms load value due to buffeting as it affects the overall deformation of the vehicle, and the remaining σ 's refer to rms dispersion load values that result from parametric dispersions; the subscripts indicate the parameter leading to the dispersion load, such as drag coefficient, airload distribution, structural weight, misalignments, propellant weight, and autopilot gain.

Because density appears in many of the terms of the equation of motion, the dispersion term σ_ρ is different in character from other dispersion terms. Variations in density up to as much as 40 percent from the mean density profile have been noted (ref. 48); the dispersion loads due to density variations can therefore be expected to be sizeable. When evaluating incremental variations in density, as discussed in general with respect to figure 2, density dispersion effects should be established correctly by considering all density-dependent mean loads (e.g., winds, gusts, aerodynamic misalignments, trim drag, incidence drag, and autopilot gains) as acting simultaneously. It is the usual practice, however, to treat winds and gusts separately, and thus some error may be introduced in studying density variation effects. The magnitude of this error is unknown but is judged to be small and negligible.

Local loads due to venting, compartment or tank pressurization, local buffeting, and residual pogo oscillations should also be established; except for the local buffeting loads, these loads are essentially deterministic in nature. The individual axial, shear, and bending moment loads and the local loads are then combined to yield the total axial, shear, and bending-moment loads for use in stress analysis and design. In combining the loads, the vector and random nature of the loads should be accounted for, and care should be taken to use plus or minus values for those loads that can be expressed either way so as to lead to the largest compression load, and similarly to use whatever plus or minus values are needed to lead to the largest tensile load. It should also be remembered that a correct load perturbation from density variations is obtained only if all other density-dependent loads are considered as acting simultaneously with the wind.

Means for establishing the wind and gust loads that appear in equation (5) are discussed in reference 6. The analysis should use nominal values of vehicle parameters. If wind loads are established with a number of measured profiles, care should be taken to use the air density values which existed when the profiles were taken so as to account for,

at the same time, all dispersions due to atmospheric density variations. If the actual density values related to the specific winds are not available, a standard density profile for the particular launch site should be used with a plus deviation (e.g., that includes 95 percent of all of the density profiles). Thermal deformation effects, if present, should be included in the determination of wind loads.

Because synthetic wind profiles are very coarse representations of wind profiles, it is recommended that the entire load-combining process be simplified consistently when synthetic profiles are used. Thus, the sophistication of other load analyses and dispersion calculations should be relaxed when such profiles are used; the simplification felt appropriate should be established by negotiated agreement between project management and load analysts.

Measured or synthetic directional wind-speed profiles should be used wherever possible. If directional profiles are unavailable, the scalar (nondirectional) profiles should be applied at various relative azimuth angles (e.g., head winds, tail winds, and cross winds). Directional winds should be divided into pitch plane and yaw plane components, and the vehicle response should be determined under the simultaneous action of these two components.

Reference 6 treats gust loads mainly in terms of a discrete-gust concept; however, when further information is available about the power spectral makeup of gusts for ascending vehicles, gusts should be treated by power spectral methods. In this event, the gust load would be considered in a dispersion sense, and would be included as a σ_G^2 term in equation (6) and not be included in equation (5).

It should be established whether buffeting is extensive enough to affect the bending of the vehicle or whether it only affects local panel regions; if buffeting is mainly local, the buffeting load should not be included in the evaluation of equation (6) but should be introduced later in the combining treatment as a local load.

Restricted flight designs (i.e., those vehicles that cannot be flown in the more severe wind conditions because of possible structural breakup) should be treated as follows. The winds and density should be measured for these vehicles just prior to the scheduled flight and a computer run made with these measured quantities to establish deterministically the wind loads (and possibly the gust loads, depending on the detail of the wind profile used) that are likely to be experienced; nominal values of the vehicle parameters should be used in this evaluation. The results of the runs should then be used to decide whether the wind loads are within the allowed wind increment, and whether flight may proceed (fig. 6).

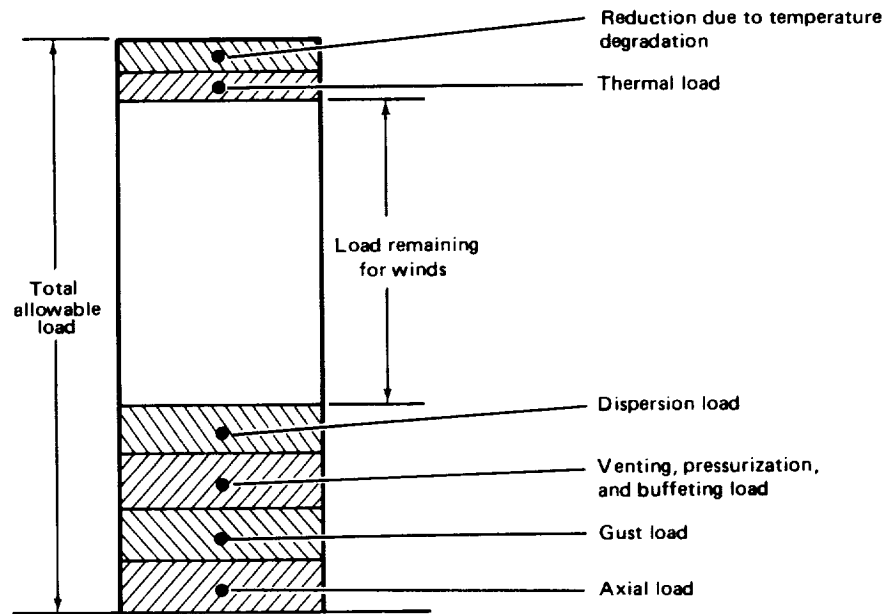


Figure 6. — Load treatment for restricted flight designs.

4.2.3 Staging

The various transient loads that occur during such staging sequences as thrust tailoff, separation forces, and ignition transients should be established as accurately as possible. Particular attention should be given to determine both tensile and compressive loads due to engine shutdown, especially with engine malfunction conditions, and change of moment at separation. Reference 4 discusses the means for establishing staging loads.

Analysis of combined staging loads should proceed along the following lines. Dynamic modeling of the vehicle for both longitudinal and side response should be performed, with response loads being established for the various nominal transient load inputs. The loads resulting from longitudinal and side response should be added deterministically, giving due attention to phase, if the input loads exhibit small variability. If the input loads indicate marked timewise variability, maximum loads due to longitudinal and side response should be added, ignoring phase. To account for dispersion in the separation loads sources, resulting response loads should be increased by some percentage factor, depending on the variability of the input and as agreed upon between project management and load analysts.

4.3 Tests

Tests to verify the load-combining procedure cannot be made directly. In lieu of this, combined-load tests should be conducted where feasible to verify structural integrity. All loads acting in combination should be included in such tests.

Flight tests should be conducted where feasible to obtain sample data on the individual load sources and sample data on combined loads to allow an indirect check of the load-combining process.

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